Integrating habitat concerns into Gordon-Schaefer model

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Abstract

In the Gordon-Schaefer model (G-S model), widely used to design fisheries management policy, only resource stock dynamic is considered and carrying capacity is constant. We propose an extension to the G-S model that incorporates the dynamics of carrying capacity as an indicator of dynamics of the marine habitats. The study yields two main findings. First, we demonstrate that habitats matter, by showing that the main outcomes of the G-S model are dramatically modified if habitats are included in the analysis. Second, through a heuristic model and simulations, we show, for the first time, that our extended model provides an appropriate framework to analyse the putative contribution of MPAs and ARs. The model presented in this article opens the way to a better understanding of the benefits of MPAs and ARs, as well as other habitat protection policies.

Keywords: Bioeconomics, Gordon-Schaefer model, Marine habitats, Artificial reefs

JEL classification: C61, C63, Q22, Q57

1 Introduction

There have been many attempts to preserve fishing resources by various management tools such as access limitations, quotas, taxes or subsidies. Most of such fisheries management recommendations stems from the traditional approach to fisheries economics (Clark, 1990, 2006) based on Schaefer (1954) and Gordon (1954). Over the years, it has become obvious that these tools have not succeeded in avoiding the severe decline of commercial species and of marine resources in general. Specifically, the economics tools do not seem fully appropriate resource conservation because of the pressure on non-target components of marine ecosystems (see for example Reiss et al. (2010) on the case of TACs). The incidental capture of targeted species and other components of the marine ecosystem or "by-catch" problem, is one of the major issues facing commercial fisheries, since it can affect the structure and function of marine systems at the population, community and ecosystem levels (Hall et al., 2000).

As a result, not only are most commercial stocks are currently overexploited (Lauck et al., 1998; Castilla, 2000; FAO, 2006), but entire trophic webs and habitats may be disrupted at the ecosystem level (Harrington et al., 2005). Recent studies such as Pikitch et al. (1998), Powers and Monk (1988), or Worm et al. (2006) promote a new vision for fisheries management. According to them, ecosystem attributes must be integrated into management and successful management cannot be achieved without a clear understanding of biological processes at an ecosystem level. A major challenge is to incorporate this new approach to marine resource management into standard mathematical models traditionally used in fisheries economics. The standard framework of fisheries economics was developed from seminal strudies by Schaefer (1954) and Gordon (1954). This model, referred to as the Gordon-Schaefer model (hereafter, G-S model), has allowed managers to obtain quantitative recommandations. In this paper, we incorporate into the G-S model ecosystem concerns such as changes in the habitat of the targeted species of the fishery.

Indeed, following Barbault and Sastrapradja (1995) and Sala et al. (2000), a major threat to marine biodiversity is habitat degradation. These authors state that, it is not possible to protect species and their ecological functions without first protecting their habitats. Burke et al. (2000) show that marine areas have endure high levels of habitat destruction with about one-fifth of marine coastal areas having been highly modified by humans. For example, coral reefs which support a high fish species diversity continue to decline. It is therefore vital to combat marine habitat degradation.

To this end, new policies have been implemented. In 1992, the European Council established the "Habitats Directive" [1] which considers the conservation of natural habitats as one of the essential objectives of general interest pursued by the European Community. For marine habitats, the directive aims at encouraging the conservation of essential habitats in order to maintain marine biodiversity in Europe. Some years earlier (1986) a similar program for the management of marine habitats was developed by the Department of Fisheries and Oceans of Canada. Its objective was an overall net gain in productive capacity of marine habitats by means of the active conservation of the current productive capacity of habitats, the recovery of damaged marine habitats and the development of habitats. To adress these ecosystem concerns, fisheries management tools like marine protected areas (hereafter MPAs, see Kar and Matsuda (1998); Sanchirico and Wilen (1999, 2001, 2005)) and artificial reefs (hereafter ARs, see Pickering and Whitmarsh (1997); Pickering et al. (1998)) were developed with the clear objective of supporting fisheries via preserved or restored ecosystems and habitats.

However, the field of fisheries economics offers no theoritical support knowledge regarding the management of marine habitats. To our knowledge, there has only been one attempt to integrate habitats into the analysis of optimal fisheries management based on the G-S model. Holland and Schnier (2006) studied the possibility of implementing an individual habitat quota system to achieve habitat conservation via economic incentives. They adapted the G-S model by integrating habitat stock endowed with its own dynamics. By simulating the model, they investigated the conditions in which an individual habitat quota regime is more cost-effective than an MPA. Although, their model establishes no connection between fish dynamics and the evolution of habitats. On the other hand, Naiman and Latterell (2005) clearly state that fish production is dynamic both on species and in habitats. Yet there is no framework incorporating this important dimension to fisheries management.

In this context, therefore the G-S model needs to be adapted. Degradation or improvement of marine habitats must be taken into account to produce new quantitiative fisheries management recommendations. It is no straightforward, however to incorporate "habitat" into the G-S model and defining "habitat" is actually beyond both the scope of this paper and the scope of economic theory. We adopt a very rough definition of habitat as a specific area or environment in which a plant or a species lives. "Habitat" provides all the basic

[1] Council Directive 92/43/EEC of 21 May 1992 on the "‘conservation of natural habitats and of wild fauna and flora".

requirements for survival. On the other hand, carrying capacity is traditionally interpreted as a maximal population level that can be supported in a given marine area. It is one of the determinants of fish stock dynamics and a major parameter in the G-S model. On the other hand, Griffen and Drake (2008) have found that carrying capacity is influenced by habitat size and quality and is correlated with extinction time: larger habitats support populations with higher carrying capacities; higher quality habitats support populations with higher carrying capacities (see also Pimm et al. (1988); Hakoyama et al. (2000)). The evolution of an area's carrying capacity results from that of marine habitats present in the area and it can be stated that there is a positive relationship between habitat and carrying capacity; if habitat in a marine area improves (degrades), so does carrying capacity in the marine area. Thus, carrying capacity can be considered as depending on natural habitat rehabilitation processes or man-made habitat rehabilitation processes (for example ARs) and on habitat alterations due to natural processes or induced by fishing.
Here, therefore we propose an extension to the G-S model that incorporates the dynamics of "habitats" through the dynamics of carrying capacity in a single-species model.

Carrying capacity now cease to be a parameter and becomes a state variable endowed with its own dynamics in our model. In this first approach, we assume that carrying capacity dynamics depends entirely on habitat dynamics. The latter assumption is clearly too simple to model the complex processes occurring in actual marine ecosystems[2]. Yet it allows us to address the question of fisheries management at ecosystem level with a relatively simple model design and to obtain some significant results. In particular, we demonstrate that ignoring habitat dynamics can lead to inappropriate design of fisheries management tools. Bionomic equilibria and optimal harvest policies are explored in the following sections using analytic models and computer simulation models that explicitly incorporate dynamics of habitat via carrying capacity dynamics.

In the next section we present our new model incorporating habitat dynamics. In section 3 biological and bionomic equilibrums are characterized and Maximum Sustainable Yield (MSY) is determined in this new framework. In section 4 the problem of optimal management is addressed and Maximum Sustainble Yield (MSY) and Maximum Economic Yield (MEY) are calculated in the model. In section 5, we build a heuristic model that allows us to compare fisheries indicators as MEY and MSY between our model and G-S

[2]There are many studies about the relationship between habitats and abundance (Gratwicke and Speight, 2005). Habitats and particularly their complexity are foundamental to explain species richness and abundance. The workshop on "'Economics and biological impacts of ARs"' organized by "'Aix Marseille University"' in 2010 addresses this issue.

model. Then, by means of simulations, we study the use of various management tools like "open access", optimal mangement, MPAs, ARs, gear restrictions, with both models. Finally, we conclude and discuss future perspectives.

2 The model

We begin by describbting the G-S model. We then detail how the model is extended so that habitat concerns can be taken into account in the analysis of optimal fisheries management, as explained section 3.

2.1 Gordon-Schaefer model

Following Schaefer (1954), the biomass x of a given fish species obeys the following equation:

$$\dot{x} = F(x) - H(x, E) \tag{1}$$

where $F(x)$ is the natural growth rate of the fish population while $H(x, E)$ is the harvest rate.
The standard assumptions on the above functions are as follows (Clark, 1990):

$H(x, E) = qxE$ where q is a constant parameter called the catchability coefficient and E is a variable called the fishing effort. More generally, the harvest function can be written as $H(x, E) = v\rho(t)E$ with v catchability coefficient per unit of density and $\rho(t)$ referred to as the mean density. When $\rho(t)$ is proportional to $x(t)$, we get the standard Schaefer model.

$F(x) = rx\left(1 - \frac{x}{K}\right)$ with r the intrinsic growth rate and K the area's environmental carrying capacity or saturation level for a given fish species. The function F is called logistic law. It was first formulated by Verhulst in 1838 in order to study population growth and assumes that growth is limited by the availability of resources like light, space, nutrients or water. In this context, the population increases at rate r up to a given K, the environmental carrying capacity.

In the context of fishery, resources for growth are provided by marine habitats that shelter fish and provide means of survival. In line with this, any degradation of habitats induced by fishing gear and resulting in disturbance of one (or more) of their functions implies a decline in the area's carrying capacity for a given fish species (Turner et al., 1999).[3] Conversely, resources and habitat can be improved through implementation of policies like MPAs or ARs, leading to increased carrying capacity.

2.2 Incorporating habitat considerations

In Gordon-Schaefer model, it is assumed that fishing activities only degrade the resource. However, as explained above, certain fishing gears also deteriorate marine habitats. Since habitats are linked to the parameter K, the fishers employing that kind of gears are also expected to impact the carrying capacity K of the marine area. We hence modify the G-S model by considering K as a state variable endowed with its *own dynamics* as follows:

$$\dot{K} = D(K) - G(E, K) \tag{2}$$

where $D(K)$ is the growth rate of carrying capacity K driven by habitat rehabilitation and $G(E, K)$ is the loss rate of K induced by habitat degradation. Since fishing has a considerable effect on the habitat and thus on the carrying capacity K of the concerned area, we focus on this aspect of habitat degradation.

$D(K)$ is assumed to reflect the growth of the fauna and flora populations in the habitats on which the targeted fish species is ecologically dependent. The function $D(K)$ embodies not only natural recovery of habitats but also artificial recovery through policies such as ARs and creation of new habitats as MPAs. A marine area being limited, it cannot support an infinite quantity of fish and thus its carrying capacity is bounded by an upper limit $K_{\max}$. In the same manner, habitat degradation signifies any alteration of habitats by natural processes or, of particular relevance here, through poor management. It is well known that some fishing techniques, like trawling, compromise habitat functions required for fish survival. Habitat degradation affects carrying capacity through the function $G(E, K)$.

Using equation (2), different situations can be depicted via the choice of functions D and G. For example, $G = 0$ represents being forced to use habitat-friendly fishing methods, or the absence of fishing in the marine area in question. In these cases, marine habitats recover and an area's carrying capacity can increase to its maximum $K_{\max}$. Similarly, if degradation processes are stronger than natural or artificial restoration of habitats, i.e. $G > D$, carrying capacity can fall to almost zero and fish can disappear from the area.

[3] We simplify by affirming that damaging habitats influences only the carrying capacity of the area. Decline in fish quality is a possible consequence of such agressive fishing and, as a result, its market price also decreases.

2.3 Extended Gordon-Schaefer model

In our model, two state variables x and K are considered, each endowed with its own dynamics:

$$\dot{x} = F(x, K) - H(x, E, K), \tag{3}$$

$$\dot{K} = D(K) - G(E, K) \tag{4}$$

with initial conditions $x(0) = x_0, K(0) = K_0$ and where functions F and H are as follows:

$$F(x, K) = rx\left(1 - \frac{x}{K}\right), \tag{5}$$

$$H(x, E, K) = vE\frac{x}{K} \tag{6}$$

In this extension to the G-S model, the link between the dynamics of fish biomass and the dynamics of habitats is taken into account by means of carrying capacity (see Figure 1). By damaging the habitats located in the area, fishing impacts carrying capacity and hence disturbs the natural growth rate of fish populations. Furthermore, the design of the extended model reflects that harvests depend on fish density subject to both fish stock dynamics and carrying capacity dynamics. The density $\rho(t)$ is here defined as the ratio $\frac{x(t)}{K(t)}$. It should be noted here that in the Schaefer equation, lower stock level implies lower harvest. With (6), we maintain this interpretation but express it in terms of density. For a given level of fish stock and a given level of fishing effort, higher carrying capacity implies lower mean density and hence lower harvests via the catchability coefficient per unit of density v.

2.4 Basic specification

In this section we specify the functions of the model (3)-(4) and describe variable behavior in this model.

To get straight comparisons with the G-S model, we start by assuming that D obeys the logistic law and G has a form similar to that of harvest function H, then

$$\dot{x} = rx\left(1 - \frac{x}{K}\right) - \frac{vEx}{K} \tag{7}$$

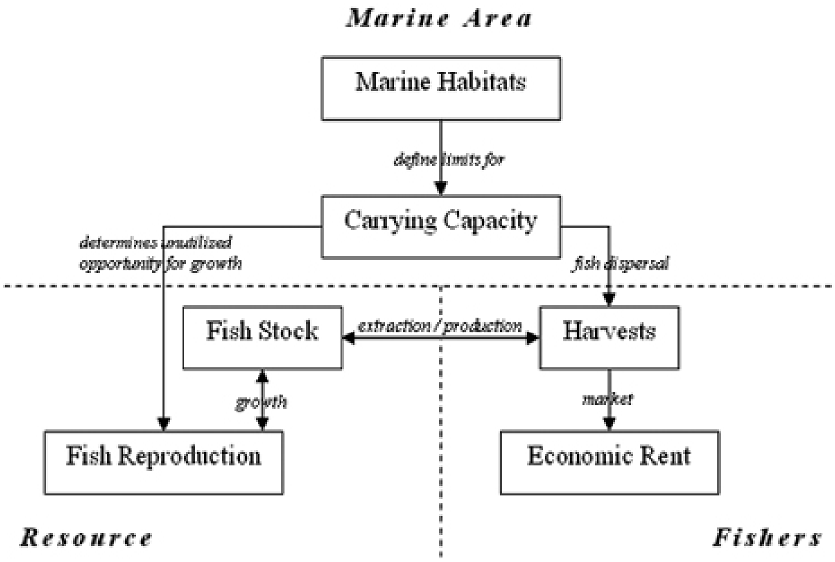

Figure 1: This scheme illustrates connexions between different components of the model. It shows the role of marine habitats in the behaviour of fish populations and hence in the formation of the economic profit of fishery.

$$\dot{K} = \tau K \left(1 - \frac{K}{K_{\max}}\right) - \gamma E K \tag{8}$$

where τ is the growth rate of K driven by habitat recovery (or "growth"), γ is the loss rate of K due to habitat alteration caused by aggressive fishing and $K_{\max}$ is the area's maximum possible carrying capacity.

Let us state the main characteristics of the model (7)-(8). Note that the assumptions concerning the dynamics of carrying capacity are interpreted from the perspective of habitats because, as noted previously, they are supposed to entirely determine the behavior of K.

1) Properties of the natural growth rate of fish population $F(x, K)$:

(1a) F has a parabolic shape and $\frac{\partial^2 F}{\partial x^2} < 0$; Given K, the population grows up to K, the saturation level.

(1b) $\frac{\partial F}{\partial K} > 0$ and (1c) $\frac{\partial^2 F}{\partial K^2} < 0$;

According to (1b), fish biomass grows faster in a marine area with larger carrying capacity. This means that higher availability of habitats encourages fish reproduction. (1c) indicates that the contribution of K to fish biomass growth rate F decreases as K

increases.

2) Properties of the harvest function $H(x, K, E)$:

(2a) $\frac{\partial H}{\partial x} > 0$, (2b) $\frac{\partial H}{\partial E} > 0$ and (2c) $\frac{\partial H}{\partial K} < 0$;

H can be interpreted as a production function with constant returns to scale, with E and x the "factors of production". (2a) and (2b) are the usual conditions : the output increases with increasing inputs E and x. (2c) can be interpreted as follows: for a given level of fish stock x and a given level of fishing effort E, higher carrying capacity leads to a lower mean density of fish, which is why it is more difficult to catch them.

3) Properties of the carrying capacity growth rate $D(K)$:

(3a) D has a parabolic shape and $\frac{\partial^2 D}{\partial K^2} < 0$;

Since habitat recovery corresponds to the growth of plant and animal communities, on which the fish species in question is ecologically dependent, it is relevant to adopt the same assumptions as for the fish growth rate F. There is a certain level of these plant and animal populations beyond which their growth rate decreases due to environmental saturation[4].

4) Properties of the loss rate $G(K, E)$ of the area's carrying capacity:

(4a) $\frac{\partial G}{\partial K} > 0$ and (4b) $\frac{\partial G}{\partial E} > 0$;

For G we adopt the same assumptions as for the harvest function H. (4a) means that larger habitats, and hence greater carrying capacity, provide more opportunities for habitats to be impacted by fishing, which implies higher losses in K. In the same vein, (4b) states that the higher the fishing pressure E on habitats, the more serious the damage inflicted on them and thus the higher the losses in K.

3 Equilibrium analysis

3.1 Biological equilibrium with harvesting

Equilibria are determined and behavior of steady-states is analyzed. For this purpose, let us consider that the fishing effort E is a parameter and analyze the solution of the system of equations $\dot{x} = \dot{K} = 0$. Then the steady states of (7)-(8) are $x_1^* = 0$, $x_2^* = K^* - \frac{v}{r}E$ and $K_1^* = 0$, $K_2^* = K_{\max}(1 - \frac{\gamma}{\tau}E)$. However, K_1^* is not acceptable because of the form of the harvest function H. Hence system (7)-(8) has only two steady states (x_1^*, K_2^*) and (x_2^*, K_2^*). The first one is trivial and we focus on the positive equilibrium point (x_2^*, K_2^*).

[4] One of the reasons of saturation is that any marine area is geometrically limited. We assume that this saturation threshold can be expressed in terms of carrying capacity.

We now look at the behavior of the system at the steady state. To do this, the system of equations (7)-(8) is linearized at (x_2^*, K_2^*). Then, we write the Jacobian of the system $V(x_2^*, K_2^*) = \begin{pmatrix} \frac{vE}{K_2^*} - r & r - \frac{vE}{K_2^*} \\ 0 & \gamma E - \tau \end{pmatrix}$.

Due to the condition of positivity of x_2^* and K_2^*, we obtain negative eigen values $\frac{vE}{K_2^*} - r < 0$ and $\gamma E - \tau < 0$. As a result, (x_2^*, K_2^*) is locally asymptotically stable.

The behavior of the model at the steady state depends on the fishing effort E. If no fishing takes place, i.e. $E = 0$, for non zero initial carrying capacity and fish stock, both attain their maximum $x^* = K_{\max}$, $K^* = K_{\max}$. Fish stock and carrying capacity are positive at the steady state if the effort $E < K_{\max}/(\frac{\gamma K_{\max}}{\tau} + \frac{v}{r})$.

As we can see, the level of fish stock x at equilibrium depends on the area's carrying capacity K. It increases with K and can collapse if effort E is such that $E = \frac{rK}{v}$. Thus, for higher K, higher effort can be applied without leading to a total shortage of the fish population. Conversely, for lower K, lower effort can result in fish collapse. Furthermore, in addition to the usual constraint of fish stock positivity $E < \frac{rK}{v}$, the fishing effort must be sufficiently low to keep the carrying capacity above zero, i.e. $E < \frac{\tau}{\gamma}$, in order to avoid a shortage of fish in the area.

The above analysis demonstrates that incorporating the dynamics of carrying capacity provides a powerful tool to address the issue of fisheries conservation. Through its equilibrium behavior, the model exhibits such features of marine ecosystems as the potential for fish stock to collapse because of the destruction of habitats leading to decreased carrying capacity. Thus, the biological and the economic arguments justifying habitat conservation become obvious. The resource cannot be preserved without protecting habitats.

3.2 Biological and economic overfishing

Following Gordon (1954), under open access the fishing effort E increases while the economic rent is positive because additional fishing units are attracted to the fishery. When the rent is negative, some fishing units withdraw from the fishery, reducing the level of effort. Hence, in the open-access fishery effort tends to reach the bionomic equilibrium where the rent dissipates.

Here the economic rent R is represented by the following function:

$$R(x, K, E) = p\frac{vEx}{K} - cE \tag{9}$$

where p is the constant price per unit of harvested fish and c is the constant cost per unit of effort. Price p and cost c are exogenous.

The bionomic equilibium is attained at
$x_\infty = \frac{cK_\infty}{pv}$, $K_\infty = K_{\max}/\left(1 + \frac{r\gamma K_{\max}}{\tau v}(1 - \frac{c}{pv})\right)$ and
$E_\infty = K_M\left(1 - \frac{c}{pv}\right)/\left(\frac{v}{r} + \frac{\gamma K_M}{\tau}\left(1 - \frac{c}{pv}\right)\right)$.

As in the G-S model, the effort E_∞ leading to rent dissipation depends on the economic parameters of the fishery p, c and catchability coefficient v as well as on the intrinsic fish growth rate r. However, in our model and as expected, it also depends on the parameters τ and γ describing the dynamics of carrying capacity. Parameters c and γ are negatively related to E_∞ whereas p, r, τ and $K_{\max}$ are positively related to it.

Clearly, in the model incorporating habitat considerations, equilibrium stock level and equilibrium effort differ from those in the G-S model . Other things being equal, for a higher rate of habitat rehabilitation (implying higher τ), higher effort E_∞ can be supported by the fishery at equilibrium. Similarly, a higher habitat degradation rate leads to lower E_∞. There is hence a strong link between habitat and fishing effort. Let us propose the following framework to compare the standard G-S model and our extension. The carrying capacity in the G-S model is taken to be the initial condition in our extended G-S model. It is noted as K_0. The density function is supposed to take the following form: $\rho(t) = x(t)/K_0$. In our variation of the G-S model, this definition of carrying capacity corresponds to the initial carrying capacity $K(0) = K_0$. In our notations, the effort at bionomic equlibrium calculated on the basis of the G-S model can be written as $E_\infty^{GS} = \frac{r}{v}K_0(1-\frac{c}{pv})$. Comparing it with effort that we obtained with the extension, it is easy to see that our model predicts that the rent dissipates at a lower effort than that stated by the G-S model. Supposing that our formalization of the fishery better describes the functionning of real ecosystems, Gordon's recommendation to limit the access to the resource by E_∞^{GS} is not sufficient to avoid the dissipation of the rent.

It is well known that bionomic equilibrium describes the situation of economic overfishing in which an excessive level of effort leads to a zero rent situation, although it can be positive for lower effort levels (Clark, 1990). Another type of overexploitation addressed in Clark (1990) is the biological overfishing that occurs if the level of fish stock is lower than the Maximum Sustainable Yield (MSY). Given K and for any given level of fish stock x below K, there is a level of harvest H such that $H = F(x)$ and H can be harvested in perpetuity without altering the stock level. MSY is achieved for the population level

x where the function F reaches its maximum. By definition, $H_{MSY} = maxF(x)$. These conclusions are now discussed in our model. In this case, sustainable harvest $H(x_2^*, K_2^*, E)$ is maximized at

$$x_{MSY} = K_{MSY} - \frac{v}{r} E_{MSY},$$
$$K_{MSY} = K_{\max} \sqrt{v / \left(\frac{r\gamma K_{\max}}{\tau} + v \right)},$$
$$E_{MSY} = \frac{\tau}{\gamma} \left(1 - \sqrt{v / \left(\frac{r\gamma K_{\max}}{\tau} + v \right)} \right).$$

Similarly to the G-S model, the effort level that maximizes the sustainable harvest depends only on parameters specific to fish stock and to carrying capacity dynamics. Note also that the level of carrying capacity at which MSY is attained is not its maximum $K_{\max}$. This result is not suprising because K_{MSY} trades off posititive impact of K on harvest function H via fish stock x and its negative relation to fish concentration. On the other hand, the MSY recommendation calculated on the basis of the G-S model is to exert the effort $E_{MSY}^{GS} = \frac{rK_0}{2v}$. Since the model does not take into account the evolution of habitats, i.e. parameter K_0 is considered as constant, no recommendations are given regarding area's carrying capacity. As a result, if K_0 is lower than K_{MSY}, then the MSY in the sense of our model is not achieved and the resource faces biological overexploitation. Conversely, if K_0 is higher than K_{MSY} the fish stock stabilizes at a level higher than x_{MSY}.

This result is very important, because it illustrates how MSY based on the G-S model could overestimate the capacity of the resource to support fishing activities. This is consistent with the widely observed failure of current management tools using MSY which stems from the G-S model to preserve fisheries, and underlines the need to integrate habitats into the design of management plans, as put forward by many recent studies (see for instance Naiman and Latterell (2005)).

4 Optimal harvesting

MSY guarantees the absence ofbiological overfishing. However, it does not guarantee that the resource is not economically overexploited. We hence search for optimal harvesting policy that maximizes the total discounted net revenues of a fishery.

4.1 Economic interpretation of necessary optimality conditions

Consider a sole owner for this fishery (government agency or private firm), having complete knowledge of and control over the fish population. According to economic theory, the owner of the resource seeks to maximize the total discounted present value of economic profits. In our framework, we get the following optimization problem:

$$\underset{0\leqslant E\leqslant E_M}{Max}\ J\{E\} = \int\limits_0^\infty e^{-\delta t} R(x,E,K)dt \tag{10}$$

$$\begin{gathered}\dot{x} = F(x,K) - H(x,E,K),\\ \dot{K} = D(K) - G(E,K),\\ x(0) = x_0,\\ K(0) = K_0\end{gathered}$$

where E is a control variable and δ denotes the discount rate.

Integration of the dynamics of carrying capacity into the model provides new insight into the interpretation of the objective functional. The owner of the resource takes into account, among other things, the degradation of habitats caused by aggressive fishing through the dynamics of carrying capacity, when he decides on effort policy. Economic profit is now determined not only via the usual two factors, E and x, but also via a new factor, potentially impacting profits, K.

Optimal fisheries management can be viewed as a problem of optimal strategy for investment in assets in order to maximize the profitability of the fishery. In this case, the objective of the resource owner is interpreted in terms of capital assets. He expects the asset to earn dividends. Contrary to the G-S model, here there are two capital assets - fish stock and carrying capacity - where the latter influences the former [5]. In order to solve this maximization problem, we build its Hamiltonian:

$$\mathcal{H}(x,K,t,E,\lambda,\mu) = R(x,K,E) + \lambda(F(x,K) - H(x,K,E)) + \mu(D(K) - G(K,E)), \tag{11}$$

where, as usual, $\lambda(t)$ can be interpreted as the shadow price of a fish "in the sea" and $\mu(t)$ as the shadow price of the carrying capacity of the marine area.

Three terms on the right side of the expression (11) are value flows: the first denotes the flow of profits at time t in the objective functional J; the second can be viewed as the investment flow in the fish stock x at time t ; the last term is a new one and denotes the flow of investment in carrying capacity K at time t. Thus the Hamiltonian $\mathcal{H}(.)$ represents the total rate of increase of profits and of both capital assets.

[5] The possibility of the inverse is not taken into account in our model.

Along with the two capital assets, two types of production are involved in the Hamiltonian $\mathcal{H}$. First, fishing units "produce" fish by harvesting. Second, they accidentally "remove" a certain number of habitats due to agressive fishing (for instance, removal or scattering of non-target benthos in the case of bottom-fishing gear). Since removal of habitat substrate, fauna or flora reduces carrying capacity, we can speak of "removal" of carrying capacity. The first is a product that can be sold on the market, whereas the second can be viewed almost as a bycatch.

Thus, the optimal control $E(t)$ must maximize the rate of increase of total assets. Given the linear form of the harvest and cost functions (see equations (6) and (9)), the Hamiltonian (11) depends linearly on E with coefficient

$$\sigma = p\frac{\partial H}{\partial E} - c - \lambda\frac{\partial H}{\partial E} - \mu\frac{\partial G}{\partial E} \tag{12}$$

referred to as the switching function. In this case three solutions for E are possible: either the extremes 0 or E_M, or an interior solution E^*. When σ is positive, i.e. the shadow prices λ and μ are sufficiently low, there should be as much fishing as possible. When σ is negative, i.e. the shadow prices λ and μ are sufficiently high, there should be no fishing. When σ is nul, the control E should be set at its "singular value" E^*.

With respect to this, by the Pontryagin conditions, we have :

$$\dot{\lambda} = \delta\lambda - \frac{\partial \mathcal{H}}{\partial x} = \delta\lambda - p\frac{\partial H}{\partial x} - \lambda\left(\frac{\partial F}{\partial x} - \frac{\partial H}{\partial x}\right), \tag{13}$$

$$\dot{\mu} = \delta\mu - \frac{\partial \mathcal{H}}{\partial K} = \delta\mu - p\frac{\partial H}{\partial K} - \lambda\left(\frac{\partial F}{\partial K} - \frac{\partial H}{\partial K}\right) - \mu\left(\frac{\partial D}{\partial K} - \frac{\partial G}{\partial K}\right). \tag{14}$$

For singular control we obtain:

$$(p-\lambda)\frac{\partial H}{\partial E} = c + \mu\frac{\partial G}{\partial E}. \tag{15}$$

This equation states that the last unit of effort is such that the net value of the marginal product (its market price if caught minus its shadow price if uncaught) equals marginal user cost. The marginal user cost consists of the marginal cost of effort and the cost due to damaging marine habitats (shadow value of "removed" carrying capacity).

Write (13) and (14) as:

$$(p-\lambda)\frac{\partial H}{\partial x} + \dot{\lambda} = \delta\lambda - \lambda\frac{\partial F}{\partial x}, \tag{16}$$

$$(p-\lambda)\frac{\partial H}{\partial K}+\dot{\mu}=\delta\mu-\lambda\frac{\partial F}{\partial K}-\mu\left(\frac{\partial D}{\partial K}-\frac{\partial G}{\partial K}\right). \tag{17}$$

The left-hand side of the expression (16) is the marginal net payoff from an uncaught fish i.e. the value of the marginal product of a fish in the sea plus gains from fish capital. The right-hand side is the marginal net cost of an uncaught fish i.e. the "financial cost" of an uncaught fish minus (plus) the value of "appreciation" (depreciation) at the "biological own rate of interest".

In the same manner, the left-hand side of (17) is recognized as the marginal net payoff from the carrying capacity not impacted by fishing. The right-hand side is the marginal net cost. There are four terms describing user costs:

- "financial cost" of not "removing" carrying capacity,
- plus (minus) value of depreciation (appreciation) of fish capital,
- plus (minus) value of depreciation (appreciation) of carrying capacity capital,
- plus (minus) value of marginal increase (decrease) of carrying capacity loss rate induced by fishing.

To summarize, taking habitats into consideration through carrying capacity results in a more complex optimization problem. The regulator has to find a tradeoff not only between profits from a fish being caught and the ensuing loss in fish capital, but also between economic benefits derived from damaging habitats and loss of carrying capacity capital.

4.2 Optimal steady state

We seek now to characterize steady state in this optimal problem. In view of the model specification (7)-(8), the Hamiltonian (11) is rewritten as:

$$\mathcal{H}=\left(\frac{pvx}{K}-c\right)E+\lambda\left(rx\left(1-\frac{x}{K}\right)-\frac{vEx}{K}\right)+\mu\left(\tau K\left(1-\frac{K}{K_{\max}}\right)-\gamma EK\right). \tag{18}$$

The switching function and co-state equations are as follows:

$$\sigma=\frac{pvx}{K}-c-\frac{\lambda vx}{K}-\mu\gamma K; \tag{19}$$

$$\dot{\lambda} = \left(\delta - r + \frac{2rx}{K} + \frac{vE}{K}\right)\lambda - \frac{pvE}{K}; \tag{20}$$

$$\dot{\mu} = \left(\delta - \tau + \frac{2\tau K}{K_{\max}} + \gamma E\right)\mu - \left(\frac{rx^2}{K^2} + \frac{vEx}{K^2}\right)\lambda + \frac{pvEx}{K^2}. \tag{21}$$

Since, with more than one state equation, the Pontryagin conditions are considerably more complicated, we focus attention on the interior equilibrium solution. We hence equalize state, costate and switching equations to zero:

$$\dot{x} = 0 \implies x = K - \frac{vE}{r}; \tag{22}$$

$$\dot{K} = 0 \implies K = K_{\max}\left(1 - \frac{\gamma E}{\tau}\right); \tag{23}$$

$$\dot{\lambda} = 0 \implies \lambda = \frac{pvE/K}{\delta + f}; \tag{24}$$

$$\dot{\mu} = 0 \implies \mu = \frac{\lambda x}{K}\left(\frac{r - \delta - f}{\delta + g}\right); \tag{25}$$

$$\frac{pvx}{K} - c - \frac{\lambda vx}{K} - \mu\gamma K = 0, \tag{26}$$

where $f = -\left(\frac{\partial F}{\partial x} - \frac{F}{x}\right) = \frac{rx}{K}$ and $g = -\left(\frac{dD}{dK} - \frac{D}{K}\right) = \frac{\tau K}{K_{\max}}$.

The expression (22) represents the standard condition of sustainable yield H that can be harvested while maintaining a fixed population level x. In similar way, equation (23) describes sustainable a amount G of carrying capacity that can be lost while maintaining a fixed level K.

It is obvious that the shadow price λ is strictly positive. If $E < \frac{rK}{q}$ (condition of fish stock positivity), meaning that a fish in the sea has a nonzero value. Therefore, the regulator is incited to invest in the resource's future productivity and not to harvest all the fish instantaneously. The positivity of μ is not as obvious: it depends on the relationship between parameters r, δ and f. The holder of carrying capacity capital is incited to invest in it if $r > \delta + f$. If $\delta \geqslant r$, which means in simple language that money-in-the-bank at interest rate δ grows faster (or at the same rate) than a fish in the sea. This makes the option of fishing at the risk of decreasing the carrying capacity of the marine area more attractive than trying to avoid losses in carrying capacity for future profits.

By virtue of (24) and (25), the equation (26) is rewritten as

$$x\left(1-\frac{vE/K}{\delta+f}-\frac{\gamma E(r-\delta-f)}{(\delta+f)(\delta+g)}\right)=\frac{cK}{pv}. \tag{27}$$

When the future is entirely discounted so that $\delta=+\infty$, the equation (26) simplifies to $x=\frac{cK}{pv}$, which corresponds to the dissipation of economic rent. It also can be verified that the case of $\delta=0$ where future revenues are weighted equally with current revenues corresponds to the maximization of sustainable rent. Moreover both x^* and K^* satisfying (27) decrease with increasing δ toward x_∞ and K_∞ respectively. Our problem therefore possesses an equilibrium solution verifying the necessary Pontryagin conditions.

After some calculations we get

$$x^*=K_{\max}-\left(\frac{v}{r}+\frac{\gamma K_{\max}}{\tau}\right)E^*, \tag{28}$$

$$K^*=K_{\max}\left(1-\frac{\gamma E^*}{\tau}\right), \tag{29}$$

$$\lambda^*=\frac{pvE^*}{K_{\max}(\delta+r)-\left(v-\frac{\gamma K_{\max}}{\tau}(\delta+r)\right)E^*}, \tag{30}$$

$$\mu^*=\frac{\lambda^*x^*}{K^*}\left(\frac{vE^*/K^*-\delta}{\delta+\tau-\gamma E^*}\right), \tag{31}$$

where E^* is a root of the following polynomial of degree 3:

$$a_0E^3+a_1E^2+a_2E+a_3=0, \tag{32}$$

with

$a_0=-\gamma[(r\gamma K_{\max}+\tau v)^2-r\gamma K_{\max}\frac{c}{pv}(\delta\gamma K_{\max}+r\gamma K_{\max}+\tau v)]$;

$a_1=(r\gamma K_{\max}+\tau v)(\delta^2\gamma K_{\max}+\tau(3r\gamma K_{\max}+2\tau v)+\delta(2\tau v+\gamma K_{\max}(r+\tau)))-$
$-r\gamma K_{\max}\frac{c}{pv}(\delta^2\gamma K_{\max}+\tau(3r\gamma K_{\max}+2\tau v)+\delta(\tau v+\gamma K_{\max}(r+3\tau)))$;

$a_2=\tau K_{\max}[r\frac{c}{pv}(2\delta^2\gamma K_{\max}+\tau(3r\gamma K_{\max}+\tau v)+\delta(2r\gamma K_{\max}+3\tau\gamma K_{\max}+\tau v))-$
$(3r\tau(r\gamma K_{\max}+\tau v)+\delta^2(2r\gamma K_{\max}+\tau v)+\delta(2r\gamma K_{\max}(r+\tau)+\tau v(3r+\tau)))]$;

$a_3=r\tau^2K_{\max}^2(\delta+r)(\delta+\tau)\left(1-\frac{c}{pv}\right)$.

The term a_3 is positive due to the natural constraint of nonnegative sustainable economic rent that is satified for $\frac{c}{pv} < 1$. Thus„for any set of parameters such that $a_0 < 0$, we can guarantee that this polynomial has at least one positive root. Imposing negativity on a_0 means constraining the ratio $\frac{c}{pv}$ by some upper bound i.e.

$$\frac{c}{pv} < \frac{(r\gamma K_{\max}+\tau v)^2}{r\gamma K_{\max}(\delta\gamma K_{\max}+r\gamma K_{\max}+\tau v)}.$$

The equation (32) can have up to three real positive solutions, one of which is the optimal singular control. It is not easy to interpret the equilibrium solution from an economic point of view. Furthermore, it seems to be difficult to determine the optimal approach path, unlike the one-dimensional model for which the optimal transition is the most rapid approach path. What we do know is that it consists of bang-bang (when the control variable takes on its extreme values) and singular controls. In Appendix A, we calculate optimal steady state solution for a given set of model parameters (their values are presented in Table 1). We give results for three different values of discount rate δ (see Table 3). In this numerical example, we obtain a unique solution to (22)-(26).

5 What the simulations reveal?

This section presents results obtained using an heuristic model to simulate[6] our extended G-S model that permits habitats to be taken into account. The values of model parameters are given in Table 1.

In the first simulation we observe what happens when recommendations yielded by G-S model such as MSY and MEY are applied in the framework of the extended model (see Table 2). The goal of the second simulation is to show how the extended G-S model provides an appropriate framework to explore ecosystem based management tools more specifically MPAs ans ARs.

Simulations take equations (7)-(8) as baseline model.

$$\dot{x} = rx\left(1 - \frac{x}{K}\right) - \frac{vEx}{K}, \tag{33}$$

$$\dot{K} = \tau K\left(1 - \frac{K}{K_{\max}}\right) - \gamma EK \tag{34}$$

where $x(0) = x_0$ and $K(0) = K_0$

[6]Simulations were performed via the modelling environment ModelMaker.

Table 1: Model parameters.

Ecological parameters	Value	Unit
r	$0,5$	year^{-1}
τ	$0,01$	year^{-1}
γ	$0,00001$	year^{-1}
$K_{\max}$	5000000	kg
Economic parameters	**Value**	**Unit**
p	15	euros
c	100	euros per unit of effort
v	20	year^{-1} per unit of density
n	$0,0001$	year^{-1}
Initial conditions	**Value**	**Unit**
x_0	200000	kg
K_0	500000	kg
E_0	170	vessel-days

Table 2: Effort levels corresponding to different reference points.

Reference point	G-S model	Extended G-S model
Bionomic equilibrium	$E_{\infty}^{GS} = 8333$	$E_{\infty} = 988$
Maximum Sustainable Yield	$E_{MSY}^{GS} = 6250$	$E_{MSY} = 910$
Maximum Economic Yield	$E_{MEY}^{GS} = 4198$	$E_{MEY} = 891$

When we assume open access to a fishery, we need to describe the dynamics of effort to implement simulations. For the sake of interpretation, the open access fishery is depicted here by the dynamic model of Smith (1968) which links the entry and exit of fishing units to the level of profitability, here $R = (\frac{pvx}{K} - c)E$. Then the effort dynamics is as follows:

$$\dot{E} = n\left(\frac{pvx}{K} - c\right)E, \tag{35}$$

where n is an adjustment parameter and $E(0) = E_0$ is initial effort. The model of Smith replicates the main result of Gordon (1954) namely that the economic rent dissipates at equilibrium if access is not regulated.

5.1 Do habitats matter?

A first set of simuations compare how "Open Access" scenario works with the extended G-S model (equations (7), (8) and (38)) and with the standard G-S model (equations (7) and (38)). At equilibrium, the stock and the carrying capacity in the extended G-S model (green curves) are lower than in the G-S model (red curves), as depicted in Figure

2. Although this result is rather technical since it arises from introducing in the model the possibility that the fishers decrease carrying capacity when they are fishing, it is yet based on real observations that carrying capacity declines when the fishers deteriorate the habitats. In light of this, we argue that habitats do matter and a policy conceived without taking into account this component of a marine ecosystem could be irrelevant.

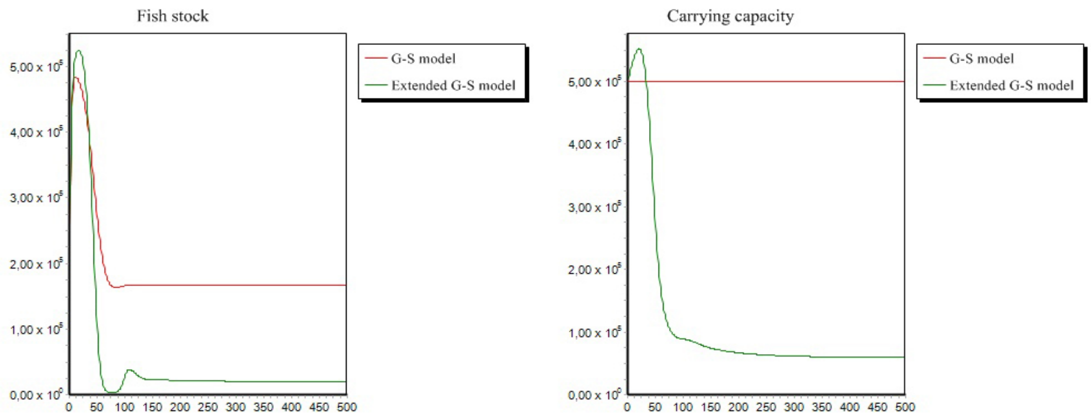

Figure 2: Open access: G-S model vs. Extended G-S model

Indicators such as MSY and MEY, which are guidelines for fisheries management, need to be carefully determined in order to design efficient management tools. They are usually based on the G-S model, where habitat issues are omitted. Suppose, as we claim, that habitats do matter; then by using the extended G-S model that integrates carrying capacity dynamics, we can expect to obtain a better description of the behavior of marine ecosystems and fishery dynamics. We show below that sticking to the G-S framework will result in ecosystem and fishery collapses because of the excessive fishing effort produced by the model.

First effort levels E_{MSY}^{GS} and E_{MEY}^{GS} corresponding to MSY and MEY, are determined from the G-S model (see Table 2); second we calculate E_{MSY} and E_{MEY} relying on the extended framework of G-S model developed herein (see Table 2). We use the parameter values in Table 1 and formulas from the previous sections. Figure 3 illustrates the behavior of the system when effort is restricted to MSY effort level. Recall that, theorically, this effort level leads to a level of catch that can be harvested in perpetuity without altering the stock of the resource. Thus, the level of fishing effort is taken as constant and equals E_{MSY}^{GS} for the red curve and E_{MSY} for the green curve. Three trajectories are simulated: fish stock, carrying capacity and economic profit. As expected, all three trajectories described by green curves converge to calculated equilibrium levels (see Table 3). Conversely, the red curves portray the collapse of the system driven by excessive fishing pressure. The same reasoning is applicable to MEY (see Figure 4). If the "true" model is the extended G-S model, applying E^{GS}_{MEY} does not imply maximization of profits but quite the contrary: profit decrease sharply until it becomes negative.

Figure 3 and Figure 4 show that leaving habitat considerations out of the analysis leads to considerably overestimated of MSY and MEY and therefore to resource collapse. If such recommendations are used in the design, for example, of a TAC regime, the limits for TACs will be several times the acceptable amount. Thus, even with TACs, fish stock and fisheries risk rapid depletion and collapse.

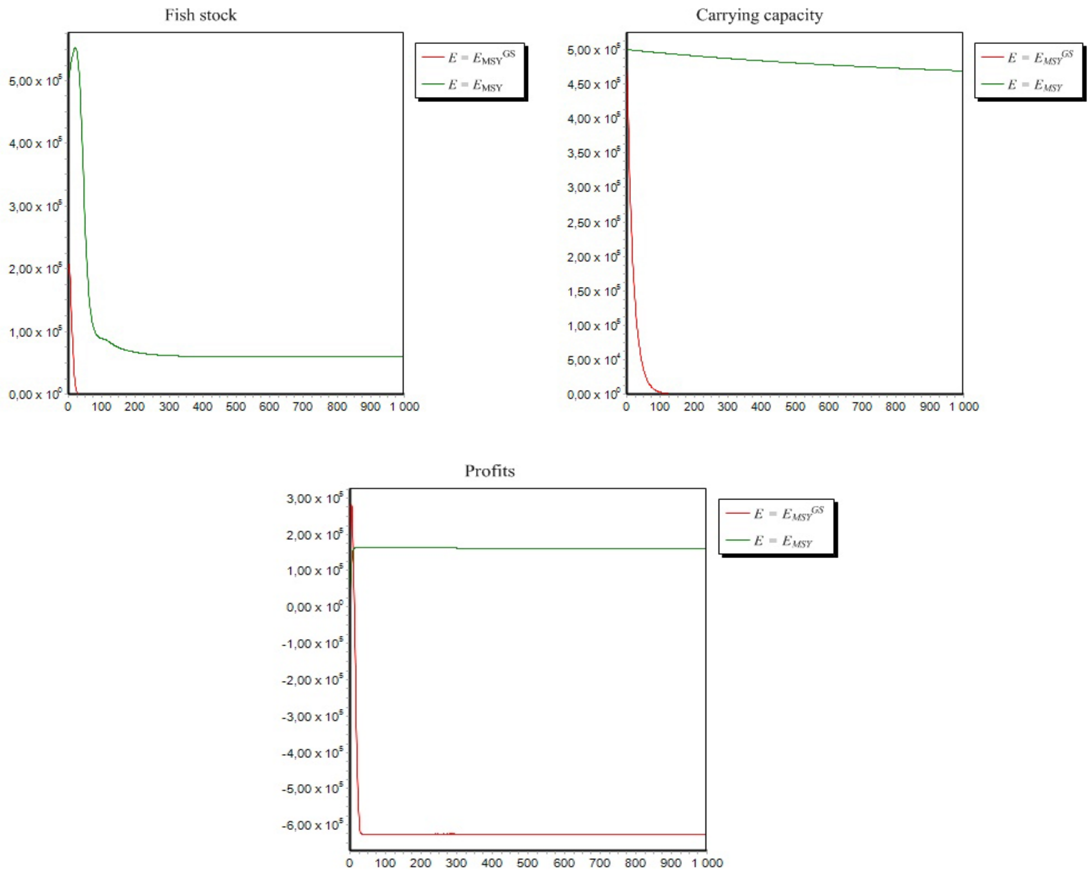

Figure 3: Maximum Sustainable Yield: G-S model vs. Extended G-S model.

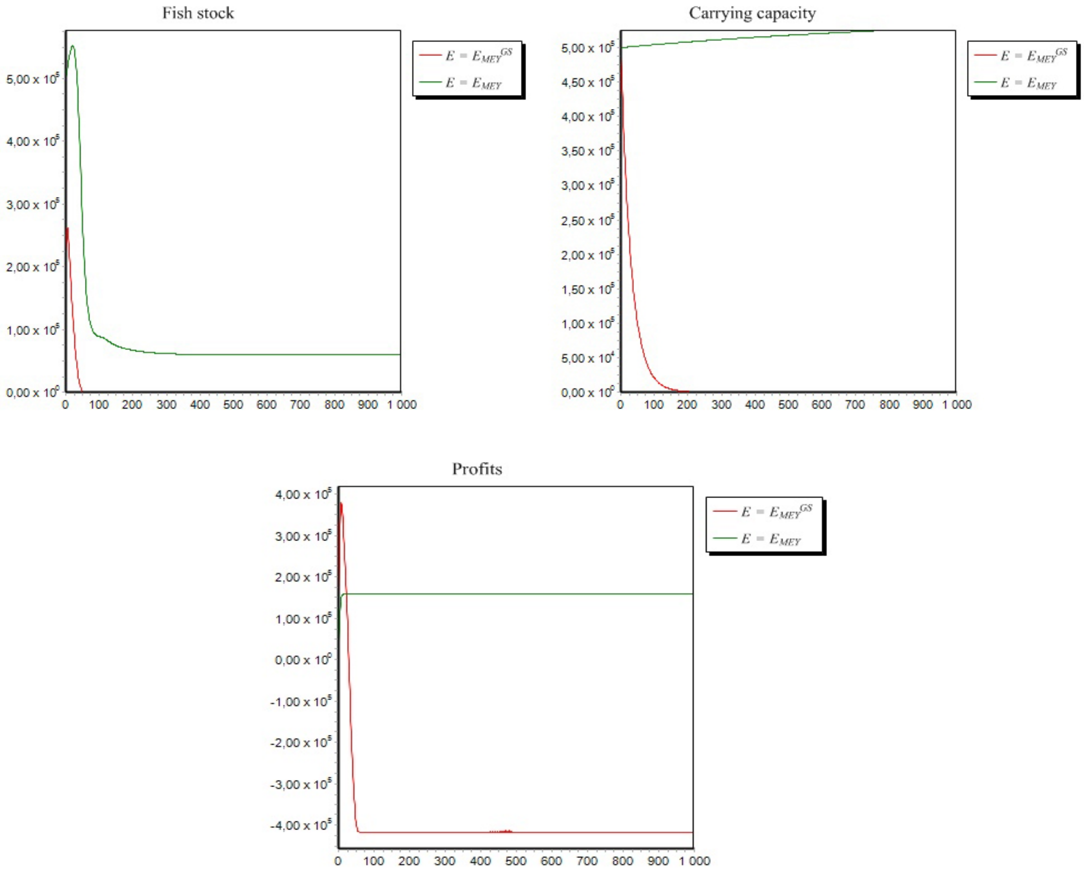

Figure 4: Maximum Economic Yield: G-S model vs. Extended G-S model.

5.2 Solving the problem of habitat management

Consider a marine area with poor habitats. In the extended G-S model, poor habitats can be interpreted by low initial level of carrying capacity, denoted as $K(0)$. In order to preserve the resource and its associated fishery, recommendations may include MPAs, gear zoning or area rotation depending on particular gear and habitat type (Guillén et al., 1994). The use of ARs has also been suggested as a way to prevent trawling which greatly damages marine habitats (see for instance, Jennings and Kaiser (1998), Turner et al. (1999)) or to favor reproduction of fish populations by providing means of survival (Pickering and Whitmarsh, 1997). This wide range of policies could not previously be properly assessed on the basis of the G-S model. Yet their assessment becomes possible using the extended model developed herein.

In the present paper, the following policies are considered: gear restriction, MPAs, ARs and optimal fisheries management (as described in the previous section). All of them focus on preserving both fishery profitability and the marine ecosystem. For resource managers, combining both objectives is the main characteristic of sustainable management.

5.2.1 Gear restriction

One way to respect the marine environment is to forbid the use of aggressive fishing gear. From this perspective, we understand by gear restriction the use of habitat-frendly techniques which have no negative impact on marine habitats. Gear restriction policy can be enforced by immersing ARs of protection that prevent the use of aggressive fishing techniques such as bottom trawling. In the open access fishery, we propose to model the impact of habitat-frendly techniques by adapting model (7)-(8) and (38) in the following manner (the second part of equation (8) disappears, i.e. loss rate $G = 0$):

$$\dot{x} = rx\left(1 - \frac{x}{K}\right) - \frac{vEx}{K}, \tag{36}$$

$$\dot{K} = \tau K\left(1 - \frac{K}{K_{\max}}\right), \tag{37}$$

$$\dot{E} = n\left(\frac{pvx}{K} - c\right)E, \tag{38}$$

where $x(0) = x_0$, $K(0) = K_0$ and $E(0) = E_0$.

Our benchmark is what we have called the baseline model (equations (7), (8) and (38)). Under gear restriction the carrying capacity of the area increases until $K_{\max}$ (green curve in Figure 5). In the short term, we observe higher economic profit than in the situation where no gear restriction is put into place (red curve). However, in the long term, the rent dissipates, as expected in the open access fishery. Yet, fish stock and carrying capacity do better than in the absence of gear restriction. Moreover, the area can support higher fishing effort, since the techniques employed are habitat-friendly and, thereby, have no impact on habitats.

5.2.2 Is it necessary to manage access to ARs?

ARs of production are usually implemented in marine areas with highly disturbed habitats. By providing additional means for fish survival, they are expected to enhance the area's

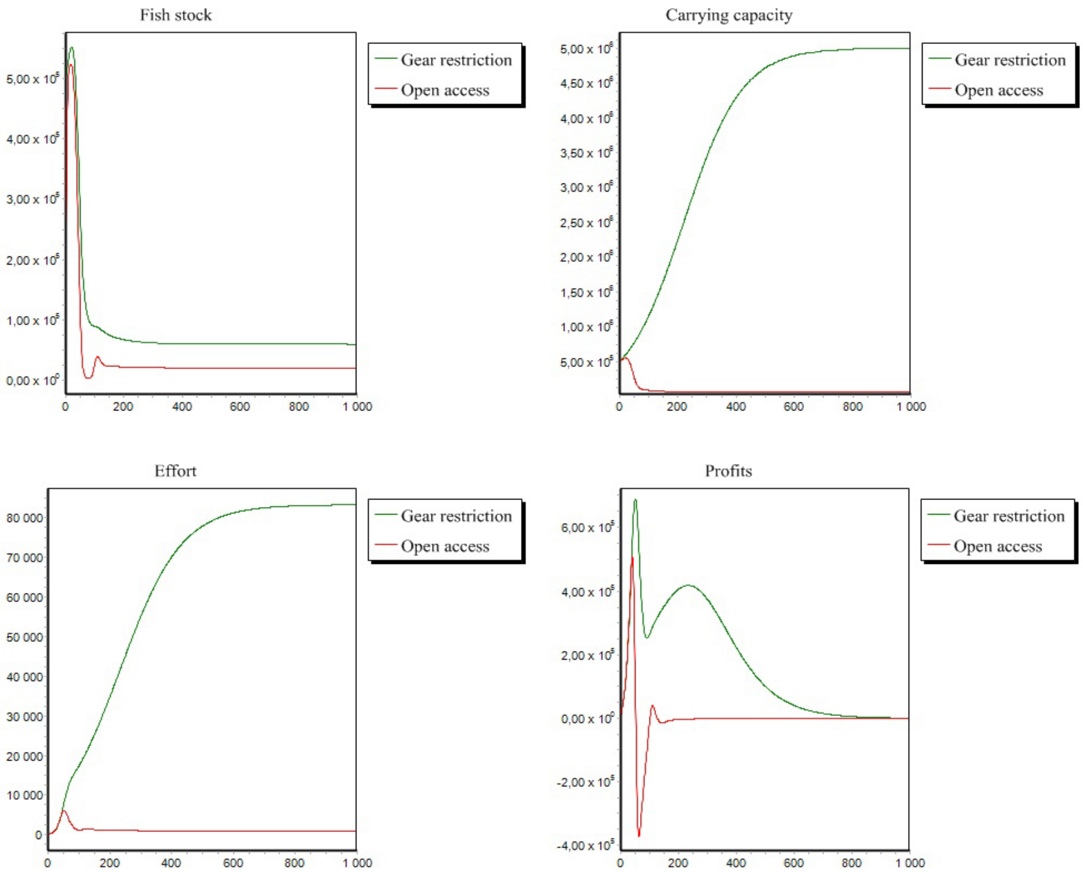

Figure 5: Open access vs. Gear restriction.

carrying capacity and fish stock. These controversial issues obviously need to be addressed in collaboration with marine biologists, as organized in the workshop at the University of the Mediterranean (Marseille) in 2010. Here, for the sake of simplicity, let us assume that ARs of production are immersed and their effect on the area's carrying capacity is instantaneous. We also assume that it is possible to estimate what size, quantity and structure of ARs will lead to instantaneous increase in carrying capacity such that $K(0) = K^*$, the optimal steady state level determined in the previous section taking discount rate $\delta = 0,01$ (see Table 3 in Appendix A).

Three scenarios are simulated in this subsection:

1. Benchmark still described by the baseline model (7)-(8) and (38) with initial conditions $K(0) = K_0$, $x(0) = x_0$ and $E(0) = E_0$;

2. ARs under open access modelled by equations (7)-(8) and (38) but where $K(0) = K^*$, $x(0) = x_0$ and $E(0) = E_0$;

3. ARs with regulated access modelled by equations (7)-(8) but where $K(0) = K^*$, $x(0) = x_0$ and $E(0) = E^*$.

Fish stock, carrying capacity, fishing effort and economic profit are the indicators observed. Their trajectories are presented in Figure 6.

When open access (red curve) and ARs under open access (green curve) are compared, several points emerge. Fish stock and carrying capacity increase in the short term in the latter scenario, followed by a decrease, so that the curve joins the red one. These momentary ecological benefits yielded by ARs open up profitable opportunities for expanding fishing effort further than with the open access scenario. This is one of the negative effects from immersion of ARs without appropriate management. Very similar effect is also revealed for MPAs (for instance, see Boncoeur et al. (2002)) which lose their positive impact when fishing effort is not regulated.

In the third scenario we set the initial fishing effort to its optimal steady state level, i.e. $E(0) = E^*$ throughout simulation (blue line). We also set initial condition on carrying capacity to its optimal level $K(0) = K^*$. Under these conditions, we simulate stock, carrying capacity and profit dynamics. Since we start with optimal steady state level, carrying capapcity remains at the same level K^* throughout the simulation. At the beginning of the simulation, fish stock and profit increase and converge to their steady state level (see Table 3 in Appendix A). As expected, this scenario leads to higher long-term profits than previous scenarios (the blue curve is higher than the red and green ones). This policy also results in a better ecological situation as measured by fish stock and carrying capacity, than previous scenarios.

This simple analysis supports the claim of Pickering and Whitmarsh (1997) that the ecological and economic benefits of ARs are short-term and dissipate in the long term, which illustrates the need to manage access to ARs areas.

5.3 Capturing the full effects of MPAs

The large body of literature on MPAs is based on the G-S model. However, MPAs are expected not only to increase fish biomass but also to favor the recovery of habitats located within their boundaries. While the first effect may be captured by the G-S model, the effect

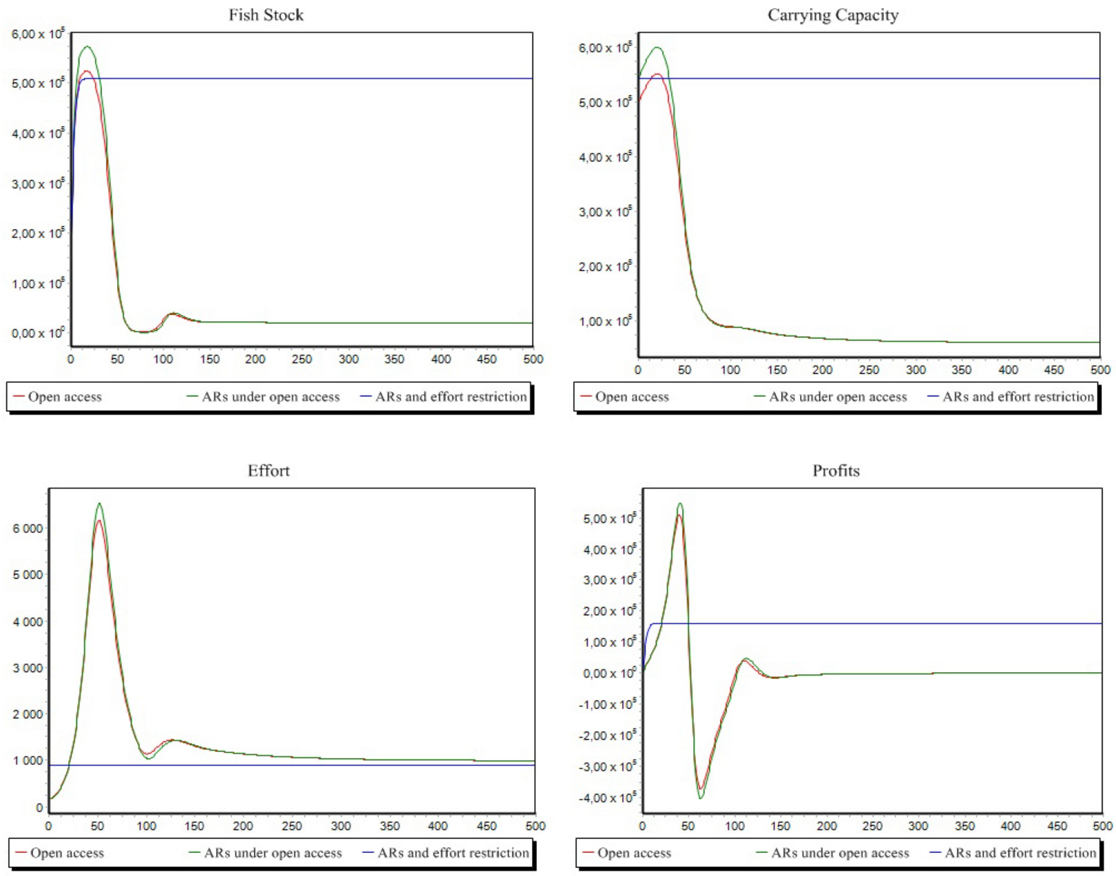

Figure 6: Open access vs. ARs under open access vs. ARs under optimal steady state effort.

of habitat conservation on fish reproduction may not. In contrast, the extended G-S model is able to give a better idea of what happens at the ecosystem level (see Figure 7)[7].

Figure 7 shows the interaction between fish stock dynamics and carrying capacity revealed by the extended G-S model and its absence in the G-S model. It is precisely this effect that we set out to capture.

6 Conclusion

First, it has been demonstrated that habitats matter since, the main outcomes of the G-S model are dramatically modified if habitat dynamics is included in the analysis. This

[7]To model MPA policy, we set effort E to 0.

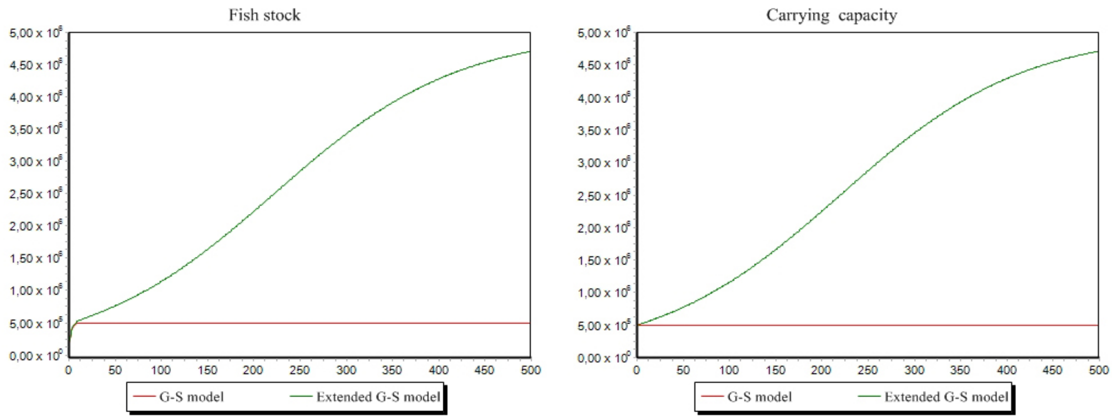

Figure 7: No-take zone: G-S model vs Extended G-S model.

result is consistent with the claims of marine biologist and marine managers that habitat deterioration is one of the most important factor in the decline of fisheries in many areas in the world. From this point of view, our extended G-S model should be more relevant to the design fishery policies. Second, through a heuristic model and simulations, we have shown how the extended G-S model provides a better understanding of common habitat protection policies like MPAs and ARs. This new model allows policy makers to set targets in terms of optimal amount of carrying capacity necessary to maximize thz profits derived from a fishery. Equilibrium analysis comparing standard fishery indicators such as resource stocks and fishing effort associated with MSY and MEY reveals how important habitats are. More precisely, we find that fishing effort associated with MSY and MEY, calculated from G-S model are systematically higher than those calculated from the extended G-S model. Thus, if habitats are indeed significantly impacted by fishing activities, we can conclude that fishery policies like TACs, where allowable catch levels are determined using the G-S model, systematically permits more harvesting than the ecosystem can support. This misspecification of effort and catch may explain why some resource stocks and their associated fisheries have collapsed. Similar misspecifications are found at biological and bionomic equilibria.

To guide policymakers in the design of habitat protection policies for optimal fisheries management, some analytical results are given herein. They imply the existence of optimal levels for both carrying capacity and fishing effort. Information on those levels could help managers to design sustainable marine policies, by taking into account both ecosystem and fishery profitability. Such policies could well include MPAs and ARs which have been applied worldwide as a means of habitat rehabilitation and protection. But they are controversial both extensively debated and extensively used.

The extended G-S model provides first theoretical support for implementing these ecosystem-based management tools because it offers an appropriate framework for analysing the economic benefits of MPAs and ARs. In others words, it explain why the Habitat Directive recommendations make sense.

Moreover, this framework allows us to distinguish between the effects of ARs and those of MPAs. In constrast to existing models, our model clearly establishes the relative effectiveness of both policies in habitat protection and shows how they achieve it.

With MPAs, fish and habitat are protected by eliminating fishing pressure in protected areas. With Ars, fish and habitat conservation are ensured through the creation of new habitats.

It is true that for the purposes of this study, we have adopted certain simplifying assumptions. While biologists themselves argue the existence of a link between habitat and carrying capacity, the latter is likely to be weaker than we suppose in this study where we have assumed that they are interchangeable. Further studies could well challenge this view, adding to the debate among biologists about production and concentration effects of ARs.

To study the concentration effect a patchy model in which resource stock will be able to move from one patch to another is required. Nevertheless, we have established a framework allowing fisheries management to be analyzed at ecosystem level. The extended G-S model we present here could be adapted to integrate heterogeneity of habitats and fish stocks by extending to going towards spatial and multi-species models.

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8 Appendix A

Level of fish stock, carrying capacity and effort at bionomic equilibrium, MSY and optimal steady state are summarized in Table 3. It also conveys the impact of discount rate δ on the optimal level of effort E^*. Recall that from previous sections, we know that optimal steady state effort is positively related to discount rate: the more the resource manager is concerned about future benefits (lower δ), the lower effort he applies. According to Table 3, fish stock and carrying capacity are negatively related to discount rate: their equilibrium values increase as δ decreases and approach the MEY level. Conversely, when δ increases, the optimal steady state coverges toward bionomic equilibrium.

Table 3: Reference points and optimal values provided by the extended G-S model.

Bionomic equilibrium	**Value**	**Unit**
x_∞	19763	kg
K_∞	59289	kg
E_∞	988	vessel-days
Maximum Sustainable Yield	**Value**	**Unit**
x_{MSY}	409005	kg
K_{MSY}	445442	kg
E_{MSY}	911	vessel-days
Optimal steady state and control $\delta = 0$	**Value**	**Unit**
x^*	508822	kg
K^*	544466	kg
E^*	891	vessel-days
Optimal steady state and control for $\delta = 0,005$	**Value**	**Unit**
x^*	170904	kg
K^*	209230	kg
E^*	958	vessel-days
Optimal steady state and control for $\delta = 0,05$	**Value**	**Unit**
x^*	77423	kg
K^*	116491	kg
E^*	977	vessel-days